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INTRODUCTION TO JUNE 1986 ISSUE OF THE CEEE TECHNICAL PROGRESS BULLETIN

This is the thirteenth issue of a quarterly publication providing information on the technical work of the National Bureau of Standards Center for Electronics and Electrical Engineering. This issue of the CEEE Technical Progress Bulletin covers the fourth quarter of calendar year 1985.

Organization of Bulletin: This issue contains abstracts for all Center papers released for publication by NBS in the quarter and citations and abstracts for Center papers published in the quarter. Entries are arranged by technical topic as identified in the table of contents and alphabetically by first author under each subheading within each topic. Unpublished papers appear under the subheading "Released for Publication". Papers published in the quarter appear under the subheading "Recently Published". Following each abstract is the telephone number of the individual to contact for more information on the topic; unless otherwise noted, this person is the first author. This issue also includes a calendar of Center conferences and workshops planned for fiscal year 1986, an announcement of recently issued standard reference materials, and a list of sponsors of the work.

Center for Electronics and Electrical Engineering: Center programs provide national reference standards, measurement methods, supporting theory and data, and traceability to national standards.

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The work of the Center is divided into two major programs: the Semiconductor Technology Program, carried out by the Semiconductor Electronics Division (formerly the Semiconductor Materials and Processes and the Semiconductor Devices and Circuits Divisions) in Gaithersburg, MD, and the Signals and Systems Metrology Program, carried out by the Electrosystems Division in Gaithersburg and the Electromagnetic Fields and Electromagnetic Technology Divisions in Boulder, CO. Key contacts in the Center are given on the back cover; readers are encouraged to contact any of these individuals for further information. To request a subscription or for more information on the Bulletin, write to CEEE Technical Progress Bulletin, National Bureau of Standards, Metrology Building, Room B-358, Gaithersburg, MD 20899 or call (301) 921-3357.

Center sponsors: The Center Programs are sponsored by the National Bureau of Standards and a number of other organizations, in both the Federal and private sectors; these are identified on page 32.

Note on Publication Lists: Guides to earlier as well as recent work are the publication lists covering the work of each division. These lists are revised and reissued on an approximately annual basis and are available from the originating division.

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SEMICONDUCTOR TECHNOLOGY PROGRAM

Silicon Materials

Recently Published

Forman, R.A., Bell, M.I., Myers, D.R., and Chandler-Horowitz, D., **The Raman Spectrum of Carbon in Silicon,** Japanese Journal of Applied Physics, Vol. 24, No. 10, pp. L848-L850 (1985).

Raman spectroscopy is used to characterize carbon-doped silicon samples prepared by ion implantation and pulsed laser annealing. Sharp lines are observed in the Raman spectra due to the ^{12}C local mode at 604 ± 1 cm^{-1} and the ^{13}C local mode at 589 ± 1 cm^{-1}. At the highest carbon densities, these local modes broaden considerably. Identical spectra are obtained from a given carbon implant whether it is annealed using a 10-ns pulsed ruby laser or a 1-μs pulsed rhosium 6G dye laser. It is shown that Raman spectroscopy has sufficient sensitivity to detect striated carbon distributions in as-grown commercial silicon. Finally, at high carbon density in the implanted and laser-annealed samples, a disorder-induced first-order Raman spectrum is observed, produced by the mass defect of the substitutional carbon.
[Contact: (301) 921-3786]

Mayo, S., Lowney, J.R., and Bell, M.I., **Evidence of Lattice Relaxation in Platinum-Doped Silicon,** Proceedings of the Materials Research Society 1985 Spring Meeting, San Francisco, California, April 15-18, 1985, Vol. 46, pp. 297-306.

The photoionization cross section of the platinum-acceptor level in silicon was measured (in relative units) as a function of photon energy. Capacitance transients due to electron emission from this level were studied in a p^+n gated photodiode at temperatures of 40, 60, and 80 K. Measurements were made over the wavelength range of 2 to 5 μm with light from a prism monochromator with a constant bandpass of 10 meV. The platinum density in the diode was about 10^{14} cm^{-3}, providing a ratio of deep to shallow (phosphorus) levels of about 1:10. The data are in good agreement with the Ridley-Amato lattice-coupling model when a Huang-Rhys parameter of S = 0.3 is used, corresponding to a Frank-Condon shift of 15 meV if an average phonon energy of 50 meV is assumed. The electronic energy of the acceptor level was 226 ± 5 meV below the conduction band, independent of temperature and in agreement with previous studies of thermal ionization. The present results provide the first clear experimental evidence of lattice relaxation associated with a deep level in silicon. However, the observed Huang-Rhys parameter is smaller than the theoretical estimates of Lowther ($S \cong 1$), suggesting that multiphonon emission may not be the only mechanism for carrier recombination involving this level.
[Contact: (301) 921-3786]

Thurber, W.R., and Lowney, J.R., **Electrical Transport Properties of Silicon,** VLSI Handbook, Chapter 14, N. G. Einspruch, Ed. (Academic Press, NY, 1985), pp. 177-190.

This short review of the electrical transport properties of silicon was written as a chapter for a VLSI handbook. The titles of the seven sections are: (1) Definition of Transport, Transport Equation; (2) Conversion Between Resistivity and Dopant Density; (3) Mobility of Charge Carriers; (4) Temperature Dependence of Resistivity and Mobility; (5) Dependence of Drift Velocity on Electric Field; (6) Minority-Carrier Mobility, Lifetime, and Diffusion Length; and (7) Mobility in an MOS Inversion Layer. The chapter includes 5 tables, 7 figures, and 35 references.
[Contact: (301) 921-3786]

Analysis Techniques

Recently Published

Baghdadi, A., and Gladden, W.K., ADC

Analysis Techniques, cont'd.

Errors in Quantitative FT-IR Spectroscopy, Proceedings of the SPIE - The International Society for Optical Engineering, Vol. 553, Fourier and Computerized IR Spectroscopy, pp. 207-209 [paper given at conference, Ottawa, Canada, June 24-28, 1985].

Analog-to-digital converters (ADCs) are the interface between the analog data actually collected by a Fourier transform infrared (FT-IR) spectrophotometer and the digital computer which processes these data. In the typical case of absorption spectra obtained using a broadband source, interferograms with a very wide dynamic range (typically on the order of 10^6:1) are required in order to produce spectra with adequate signal-to-noise ratios. This is a very demanding application, especially for a high-speed ADC. A numerical model of the effect of ADC errors, of ±1 least significant bit (LSB), shows that they can produce errors as large as 50% on the height of peaks in an absorbance spectrum at low signal levels. This result is consistent with our experimental observations. Four ADC circuit boards (all the same model) were tested in the NBS FT-IR spectrometer. At low signal levels, the disagreement between peak heights in spectra collected using the different ADC boards ranged as high as 30%, even though none of them produced the low-wavenumber distortions characteristic of inadequate ADC performance. The static transfer characteristics of each of the ADCs was determined using an automated test facility at the National Bureau of Standards. These tests showed that the boards produced errors ranging only up to 2 LSBs, in qualitative agreement with our numerical model.
[Contact: (301) 921-3786]

Gallium Arsenide Materials

Recently Published

Forman, R.A., Bell, M.I., and Mayo, S., **Rapid X-Ray Topographic Examination of GaAs Crystals**, Defect Recognition and Image Processing in III-V Compounds, J. P. Fillard, Ed. (Elsevier, Amsterdam, 1985), pp. 55-62 [proceedings of symposium held in Montpellier, France, July 2-4, 1985].

The design of a low-cost, high-throughput x-ray topography system is described, and its use in the the examination of commercial gallium arsenide (GaAs) wafers is demonstrated. Double-crystal reflection (Bragg) topographs are obtained in two minutes and transmission (Laue) topographs in fifteen minutes, using copper K_α radiation from a conventional 1-KW, fine-focus, laboratory x-ray source. Reflection topographs of typical GaAs wafers using selected diffracting planes are presented, and their relative sensitivity to various defects discussed. In crystals grown by the liquid-encapsulated Czochralski method, transmission topographs using the (022) planes display the well-known large-scale dislocation patterns produced by relaxation of thermoelastic stress.
[Contact: (301) 921-3786]

Power Devices

Released for Publication

Berning, D.W., **Power MOSFETs and Resonant Power Conversion.**

The power MOSFET is an ideal device for use with the new voltage-controlled, oscillator-driven, resonant power supplies. Care must be taken, however, that it is used correctly. Several different resonant power converter circuits are described, and details of their use of semiconductors are given. It is demonstrated that the MOSFET drain-body diode can be used in resonant converter circuits if the converter is operated at or above resonance, but should not be used if the converter is operated below resonance.
[Contact: (301) 921-3621]

Power Devices, cont'd.

Recently Published

Blackburn, D.L., **Turn-Off Failure of Power MOSFETs**, Proceedings of the 16th Annual IEEE Power Electronics Specialists Conference, Toulouse, France, June 24-28, 1985, pp. 429-435.

Experimental results of the failure of power MOSFETs during turn-off are discussed. It is shown that the electrical characteristics of these devices during failure are identical to those of a bipolar transistor undergoing second breakdown. Other comparisons of the power MOSFET failure and bipolar second breakdown are made. A nondestructive measurement system is used, allowing repeated measurements of the failure characteristics as a function of various parameters to be made on single devices. It is shown that practical, commercial power MOSFETs do not fail as a result of dV(DS)/dt (rate of rise of drain voltage) currents. Drain voltage slew rates up to 22 V/ns were studied. Other measurements show that the drain voltage at which failure occurs increases with temperature, the critical current above which failure occurs decreases with temperature, and the magnitude of the load inductance has no effect on the failure. The results of this study are consistent with the theory that activation of the parasitic bipolar transistor initiates the power MOSFET failure.
[Contact: (301) 921-3621]

Insulators and Interfaces

Released for Publication

Chandler-Horowitz, D., **Analytic Analysis of Ellipsometric Errors**, to be published as NBS Special Publication 400-78.

The purpose of this document is to give ellipsometer users a computer program that can identify the ellipsometric inaccuracies for any ellipsometer, that can be used to determine which parameters contribute the most to the overall measurement inaccuracy, and that can lead to an optimum measurement procedure. A FORTRAN program that performs the evaluation of the partial derivative expressions needed to analyze ellipsometric measurement uncertainties is listed. The program determines the uncertainty in the calculation of the refractive index of a bare isotropic substrate or the uncertainty in the determination of the thickness and refractive index of a non-absorbing film on a substrate of known refractive index. These are the two most commonly used surface models in ellipsometry performed with a single angle of incidence and a single wavelength. The program input parameters include the wavelength of the light, the angle of incidence and its uncertainty, and the uncertainties in the ellipsometric parameters DEL and PSI. They also include in the ambient-substrate model an estimated value for the substrate's refractive index, and in the film-substrate model the refractive index of the substrate and its uncertainty and values for the film's refractive index and thickness. The case of the conventional null ellipsometer using a quarter-wave plate is treated to find the uncertainties in DEL and PSI from the uncertainties in the polarizer and analyzer null values and the waveplate constants.
[Contact: (301) 921-3625]

Mountain, D.J., Russell, T.J., and Galloway, K.F., **Effect of Post-Oxidation Anneal on Electrical Characterization of Thin Oxides**, to be published in the Extended Abstracts of the Electrochemical Society 169th Meeting, Boston, Massachusetts, May 4-9, 1986.

The effect of pre- and post-oxidation treatments on thin oxide electrical characteristics was examined. Pre-oxidation clean and post-oxidation anneal (POA) times and ambients were varied. Three POA times and two gases (argon and nitrogen) were compared. Flatband voltages, oxide breakdown fields, and interface trap densities were measured for

Insulators & Interfaces, cont'd.

thin (20-nm) oxides. Interface trap densities were measured using the charge-pumping technique. Data indicate an optimum process can be designed. A sacrificial oxidation cleaning sequence and a long (120-min) POA in nitrogen gave the oxide with the best electrical characteristics.
[Contact: Thomas J. Russell (301) 921-3621]

Wachnik, R.A., **The Use of Charge Pumping to Characterize Generation by Interface Traps**, to be published in IEEE Transactions on Electron Devices.

A small rectangular pulse technique for measuring the charge pumping current has been proposed as a method to characterize interface traps near mid-gap. It is shown theoretically and experimentally that the small rectangular pulse technique can be used to predict the surface generation current measured on a MOSFET or a gated diode. This new technique has the advantage that the measured current is at least 10 to 100 times larger than the surface generation current.
[Contact: Stanley Ruthberg (301) 921-3625]

Recently Published

Chandler-Horowitz, D., **Ellipsometric Metrology of Ultrathin Films: Dual Angle of Incidence**, Proceedings of the SPIE - The International Society for Optical Engineering, Vol. 565, Micron and Submicron IC Metrology, pp. 93-95 [paper given at conference, San Diego, California, August 22-23, 1985].

Single angle of incidence ellipsometric measurements have been extended to dual angle measurements on a newly constructed multi-method precision ellipsometer in order to determine better the optical constants of a substrate. Following the measurement error analysis that was prescribed in an earlier paper for single angle of incidence and fixed wavelength measurements, the results for dual angle of incidence are presented here. Using an Explicit Error Analysis (EEA) method, involving the differentials of the measurable optical constants of the surface, it is possible to find a well-defined combination of incident angles to perform the measurement. Without a measurement error analysis, there would be no way to know what the absolute measurement uncertainty is or what angles of incidence provide optimum measurement conditions.

As was the case for the single angle of incidence measurement where there was an optimum angle of incidence to assure the highest measurement accuracy, the dual angle of incidence measurement also predicts the two optimum angles of incidence. It was found that in the case of single angle of incidence ellipsometry, the principal angle of incidence can sharply define the optimum angle for measuring bare substrates and very thin films on a substrate. Likewise, for the dual angle of incidence measurement, there can also be two sharply defined angles for certain sample surface models. Results are given for a dual angle ellipsometric measurement of the real part of the refractive index of a silicon substrate at the wavelength of 632.8 nm. A silicon dioxide film thickness between 125 and 150 nm and the two angles of incidence, 68 and 72 deg, optimized this measurement. The real part of the refractive index of the silicon substrate was found to be 3.865 ± 0.001.
[Contact: (301) 921-3625]

Dimensional Metrology

Recently Published

Kirk, C.P., and Nyyssonen, D., **Modeling the Optical Microscope Images of Thick Layers for the Purpose of Linewidth Measurement**, Proceedings of the SPIE - The International Society for Optical Engineering, Vol. 538, Optical Microlithography IV, pp. 179-187 [paper

Dimensional Metrology, cont'd.

given at conference, San Francisco, California, March 13-14, 1985].

A monochromatic, waveguide model is presented which can predict the optical microscope images of thick-layer objects including multi-layer structures; sloping, curved, and undercut edges; granular structures such as polysilicon; and asymmetric objects. The model is used to investigate the effects of line structure on the optical image, and good agreement with experimentally obtained optical image profiles is demonstrated. Implementation of the model is described by way of example, and the measurements involved in the different stages of manufacturing an MOS device are discussed.
[Contact: Robert D. Larrabee (301) 921-3625]

Nyyssonen, D., **Focused-Beam vs. Conventional Bright-Field Scanning Microscopy for Integrated Circuit Metrology,** Proceedings of the SPIE - The International Society for Optical Engineering, Vol. 565, Micron and Submicron IC Metrology, pp. 102-107 [paper given at conference, San Diego, California, August 22-23, 1985].

Current optical instrumentation being developed for critical dimension measurements in the integrated circuit industry is following one of two very different optical designs, i.e., either a focused laser beam which scans the wafer or the more conventional bright-field microscope. Traditional optical design lore has described these systems as "equivalent" based on the principle of reciprocity. More recent research has shown that the responses of these two types of systems are not equivalent for imaging of structures patterned in thin films, such as those found in integrated circuit wafer fabrication. This lack of reciprocity is the result of the dependence of the diffraction pattern on the angle of incidence of the illumination. The impact of the lack of reciprocity on the design and calibration of critical dimension measurement systems is discussed.
[Contact: Robert D. Larrabee (301) 921-3625]

Nyyssonen, D., and Postek, M.T., **SEM-Based System for Calibration of Linewidth SRMs for the IC Industry,** Proceedings of the SPIE - The International Society for Optical Engineering, Vol. 565, Micron and Submicron IC Metrology, pp. 180-186 [paper given at conference, San Diego, California, August 22-23, 1985].

The National Bureau of Standards is currently developing a new scanning electron microscope-based linewidth measurement system for future calibration of standard reference materials for the IC industry. This system incorporates a piezo/interferometric stage for precise translational motion and the monitoring of distance, improved vibration isolation, microprocessor stage control system, and computer data analysis. The specifications incorporated into the system are designed for the measurement of linewidth dimensions from 0.1 to 2 μm with a precision of 0.002 μm. The design philosophy of the system is discussed along with the current limitations of accurate edge detection in SEM-based systems.
[Contact: Michael T. Postek (301) 921-3625]

Integrated Circuit Test Structures

Released for Publication

Ellenwood, C.H., and Mattis, R.L., **Release Notes for STAT2 Version 2.00A: An Addendum to NBS Special Publication 400-75,** to be published as NBSIR 85-3292.

STAT2 is a FORTRAN program which is used to analyze and display data from microelectronic test structures fabricated on semiconductor wafers. The program reads data as a two-dimensional array, extracts sample statistical values, iden-

IC Test Structures, cont'd.

tifies outliers, calculates replacement values for outliers, and makes histograms and circular gray-tone data maps. Version 2.00A is an adaptation of STAT2 to run under Version 3.2 of the RSX-11M operating system. This operating system is used on the automatic tester which acquires the test structure data. Data can therefore be taken and analyzed on the same system.
[Contact: (301) 921-3801]

Mazer, J.A., and Ehrstein, J.R., **Effect of Sintering on the Sheet Resistance Directly Under an Aluminum/Silicon Ohmic Contact**, to be published in the Extended Abstracts of the Electrochemical Society 169th Meeting, Boston, Massachusetts, May 4-9, 1986.

Van der Pauw-type measurements with a specially designed test structure, and spreading resistance measurements, indicate that the sheet resistance directly under a sintered 1% Si-Al/Si ohmic contact is lower than the sheet resistance of the diffused layer away from the contact. These results agree with transmission-line calculations made with measurements from six-terminal Kelvin test structures, and allow an improved calculation of the circuit-loading (or front-contact) resistance.
[Contact: (301) 921-3801]

O'Keeffe, T.W., Cresswell, M.W., Linholm, L.W., and Radack, D.J., **Evaluation and Improvement of E-Beam Exposure Routines by Use of Microelectronic Test Structures**, to be published in the Extended Abstract Digest of the IEEE VLSI Workshop on Test Structures, Long Beach, California, February 17-18, 1986.

This paper describes the use of the cross-bridge test structure in conjunction with a series of interconnect test structures to assess and improve the exposure routines and procedures in the replication of submicron features. The interconnect test structures used in this experiment are resistors which include both serpentine and comb-like interconnect patterns and can be used to assess line continuity and line-to-line isolation. Results obtained during the evaluation of line continuity, resolution, linewidth, and proximity exposure effects are presented.
[Contact: Loren W. Linholm (301) 921-3801]

Radack, D.J., and Linholm, L.W., **The Application of Microelectronic Test Structures for Propagation Delay**, to be published in the Extended Abstract Digest of the IEEE VLSI Workshop on Test Structures, Long Beach, California, February 17-18, 1986.

This paper presents a comparison of the ring oscillator, the inverter chain, and the delayed Johnson counter for measurement of the propagation delay of an inverter. It describes design considerations that will improve the precision and accuracy of the measurement. Modifications to the delayed Johnson counter which allow timing comparisons to be performed on-chip are also described.
[Contact: (301) 921-3801]

Roitman, P., Suehle, J.S., Russell, T.J., and Gaitan, M., **On the Measurement of Capacitance on Wafers**, to be published in the Extended Abstract Digest of the IEEE VLSI Workshop on Test Structures, Long Beach, California, February 17-18, 1986.

Capacitance measurements of both capacitor and transistor structures can provide critical parameters for process monitoring, process modeling, device modeling, and circuit modeling. However, accurate measurements of capacitance on small devices located on large silicon wafers are very difficult. The problem is simply that very low-level analog measurements must be made at the end of a necessary system of cables and probes. Several authors have proposed building capacitance meters on the wafer, which would provide relatively high-level outputs to the external test

IC Test Structures, cont'd.

system. A method has been developed to measure capacitance on wafers directly. This work had three aspects: design of the capacitor structures, design of the probe fixturing, and instrumentation. These are discussed in turn.
[Contact: (301) 921-3621]

Schafft, H.A., Grant, T., Mandel, J., and Shott, J., **Report on an Interlaboratory Experiment**, to be published in the Extended Abstract Digest of the IEEE VLSI Workshop on Test Structures, Long Beach, California, February 17-18, 1986.

An interlaboratory experiment involving 15 laboratories and associated experiments conducted at NBS are described and the results given. The twofold purpose of the experiments is (1) to assess the reproducibility of electromigration characterizations made with equivalent test structures by laboratories using their own test methods and (2) to broaden the technical base needed to develop electromigration guidelines. Specially designed test chips (NBS-42), from one metallization lot, were used in the experiments. The electromigration test structures provided to the participating laboratories are made of unpassivated, sputter-deposited Al 1%Si on oxidized Si.
[Contact: (301) 921-3801]

Recently Published

Cresswell, M.W., Linholm, L.W., Coleman, E.S., and Partlow, W.D., **Design, Fabrication, and Testing of an Interconnect Test Structure for Evaluating VLSI Processes**, 1985 Digest of Papers, Government Microcircuit Applications Conference (GOMAC), Orlando, Florida, November 5-7, 1985, pp. 359-360.

This paper describes a systematic approach to the comparative experimental evaluation of alternative sub-micron lithographic methods using microelectronic test structures. Measurements are presented for both polysilicon and aluminum lines with design geometries of 0.6 to 2.0 μm. These structures provide unambiguous results which can be used as a tool to improve the control and performance of VLSI devices.
[Contact: Loren W. Linholm (301) 921-3801]

Lie, L., Pramanik, D., Saxena, A.N., Mazer, J.A., and Linholm, L.W., **Contact Resistance of Al-1%Si-0.5%Cu and Al/TiW/PtSi Metallization**, Proceedings of the 1985 IEEE VLSI Multilevel Interconnection Conference, Santa Clara, California, June 24-26, 1985, pp. 201-210.

The specific contact resistivity, ρ_c, has been measured using six-terminal Kelvin contact resistor test structures with contacts of varying sizes. Values of ρ_c were determined for Al-1%Si-0.5%Cu metallizations to n^+ and p^+ silicon junctions having different surface concentrations, C_o. The magnitude of ρ_c was found to decrease with increasing C_o. Values of ρ_c were also determined for Al/TiW/PtSi contact metallizations to n^+ and p^+ and were found to be at least two times lower than that for Al-Si metallization. Also, the variation of ρ_c across the wafer for PtSi was found to be less than that for Al-Si. This indicates that Al/TiW/PtSi metallizations offer advantages when compared to Al-Si metallization and can contribute to improved performance of future VLSI circuits.
[Contact: Jeffrey A. Mazer (301) 921-3801]

Linholm, L.W., Yen, D., and Cresswell, M.W., **Electrical Linewidth Measurement in the Near- and Sub-Micron Linewidth Region**, Proceedings of the Third Electrochemical Society International Symposium on VLSI Science and Technology, Toronto, Canada, May 12-17, 1985, pp. 299-308.

The measurement accuracy of the cross-bridge resistor test structure and test method has been compared to well-charac-

IC Test Structures, cont'd.

terized optical measurements for samples with near-micron and sub-micron design dimensions patterned in polysilicon films. Results are presented which show that the electrical measurements agree with the corresponding optical measurements to within the respective uncertainties of both measurements.
[Contact: (301) 921-3801]

Radack, D.J., Yao, C.T., Linholm, L.W., Galloway, K.F., and Lin, H.C., **Comparison of Microelectronic Test Structures for Propagation Delay Measurements**, Microelectronics Journal, Vol. 16, No. 6, pp. 39-46 (1985).

Propagation delay is a parameter which needs to be accurately measured for characterization of VLSI fabrication technologies and VLSI circuit design. In this experiment, three different microelectronic test structures or test circuits were used to measure the propagation delay of a minimally sized CMOS inverter. The measured results and a comparison of the test circuits are presented.
[Contact: (301) 921-3801]

Roenker, K.P., Harner, B.L., and Linholm, L.W., **An NMOS Test Chip for Instruction in Semiconductor Parameter Measurements**, Proceedings of the Sixth Biennial University/Government/Industry Microelectronics Symposium, Auburn, Alabama, June 11-13, 1985, pp. 77-81.

This paper describes an NMOS test chip, NBS-40, designed for use in a graduate-level course in the measurement of semiconductor parameters using test structures. The rationale and objectives of a parameter measurements course are discussed, and the organization and results of a course offered at the University of Cincinnati are described. The test chip layout and test structures are briefly described, and parameter measurements using the test structures are discussed. An NBS technical report describing the test chip has been prepared and is available as a student reference [NBSIR 84-2822]. Examples of recent measurement results obtained on chips fabricated through the MOSIS service are provided to demonstrate the functionality of the chip.
[Contact: Loren W. Linholm (301) 921-3801]

Schafft, H.A., **Standards for Electromigration Testing**, Final Report, 1984 Wafer Reliability Assessment Workshop, Lake Tahoe, California, September 30-October 3, 1984, pp. 91-106 (1985).

This is an edited transcript of a talk given at the 1984 Wafer Reliability Assessment Workshop which includes questions, comments, and responses. The talk described plans for an interlaboratory experiment and other work that is intended to lead to an improved way for characterizing metallizations from the point of view of electromigration. The talk outlined the steps of the interlaboratory experiment, discussed some of the design features of the test structures to be used, described the electromigration test chip, and mentioned some of the experiments that are to be performed.
[Contact: (301) 921-3801]

Schafft, H.A., Grant, T.C., Saxena, A.N., and Kao, C.-Y., **Electromigration and the Current-Density Dependence**, Proceedings of the 23d Annual International Reliability Physics Symposium, Orlando, Florida, March 26-28, 1985, pp. 93-99.

The empirical expression used to predict metallization resistance to electromigration failure involves the current density to a power of n. A value for n of 1.5 was obtained from stressing unpassivated Al-1%Si metallization test structures over a range of current densities of from 0.5 to 2.5 MA/cm^2. The steps taken to ensure an accurate estimate of the metallization stress conditions of temperature and current density to obtain this value are

IC Test Structures, cont'd.

described in detail.
[Contact: (301) 921-3801]

Process and Device Modeling

Released for Publication

Albers, J., **Some Aspects of Spreading Resistance Profile Analysis**, to be published in Emerging Semiconductor Technology, ASTM STP 960, D.C. Gupta and P.H. Langer, Eds. (American Society for Testing and Materials, 1986).

The calculation of resistivity profiles (and carrier density profiles) from spreading resistance requires the use of a correction factor. The present status of the calculation of the correction factor based upon the Schumann and Gardner multilayer solution of Laplace's equation is reviewed and discussed. Recent calculations of carrier densities from atomic densities are also discussed. In particular, the numerical solutions of the semiconductor equations are reviewed, and their implications in the interpretation of spreading resistance measurements for profiling shallow layers are presented. The limitations of the multilayer Laplace equation analysis of spreading resistance in VLSI profiling are also discussed.
[Contact: (301) 921-3621]

Bennett, H.S., **Band Structure and Density of States Changes in Heavily Doped Silicon.**

The Klauder self-energy method is applied to calculating the effects of one-body interactions among the dopant ions and the carriers in heavily doped silicon at 300 K. Many-body interactions of exchange energy for majority carriers and of correlation energy for minority carriers are estimated by interpreting optical absorption measurements and by calculations based on degenerate theory. When densities exceed 5×10^{19} cm^{-3}, one-body and many-body terms become of the same order of magnitude and should be included in calculations of band-structure changes and of properties such as carrier transport which depend on the density of states.
[Contact: (301) 921-3621]

Recently Published

Albers, J., **Monte Carlo Calculation of One- and Two-Dimensional Particle and Damage Distributions for Ion-Implanted Dopants in Silicon,** IEEE Transactions on Electron Devices, Vol. ED-32, No. 10, pp. 1930-1939 (1985) [joint issue with IEEE Transactions on Computer-Aided Design, Vol. CAD-4, pp. 374-383].

The two-dimensional distributions of particles, primary damage, Frenkel pairs, and electronic and nuclear energy loss were calculated for implantation of a line source into silicon targets by using the TRIM Monte Carlo code. In addition, the Kinchin-Pease equation was used to calculate approximate two-dimensional distributions of the Frenkel pairs (vacancy-interstitial) created by the primary displacement damage of the target atoms. These distributions allowed for the calculation of the one-dimensional distributions of these quantities for implantation into unmasked targets. The two-dimensional distributions of particles and approximate Frenkel pairs for implantation past a mask edge were constructed by means of superposition. The results are important for understanding the mass, energy, and dose dependence of implantation and the associated displacement damage.
[Contact: (301) 921-3621]

Albers, J., and Berkowitz, H.L., **An Alternative Approach to the Calculation of Four-Probe Resistances on Nonuniform Surfaces**, Journal of the Electrochemical Society, Vol. 132, No. 10, pp. 2453-2456 (1985).

An alternative approach to the calculation of four-probe resistances of structures having nonuniform resistivity is presented. The basis of this approach is the form of the spreading resistance

Process & Device Modeling, cont'd.

correction factor integral as given by Berkowitz and Lux. When this form is used, the difference of the spreading resistances involved in the four-probe resistance may be written as a simple integral which does not contain Bessel functions. Also, the derivative of the spreading resistance which is involved in the probe-spacing experiment simulation yields a simple algebraic expression. The resulting equations for the four-probe resistance and the derivative function are formally shown to be independent of both the probe radius and the probe-current density and involve only the kernel of the spreading resistance correction factor integral (sometimes known as the integrating factor). For the case of a uniform layer over insulating, conducting, or no boundaries (a semi-infinite slab), analytic expressions are derived for the four-probe resistance and the derivative function and are investigated as a function of the probe spacing. For nonuniform resistivity structures, a relatively simple numerical procedure is used for the evaluation of the four-probe resistance integral. The results obtained from this numerical technique for the four-probe resistance and the algebraic expression for the derivative function are compared with those obtained from more extensive numerical techniques and are shown to be in excellent agreement. The evaluation of the four-probe resistance and the derivative function by means of the variational technique described by Choo and coworkers is presented. A caveat concerning the use of the Gauss-Laguerre technique for calculating the four-probe resistance is also discussed.
[Contact: (301) 921-3621]

Bennett, H.S., and Fuoss, D.E., **Improved Physics for Simulating Submicron Bipolar Devices**, IEEE Transactions on Electron Devices, Vol. ED-32, pp. 2069-2078 (1985) [joint issue with IEEE Transactions on Computer-Aided Design, Vol. CAD-4, pp. 513-522 (1985)].

The conventional device physics in most numerical simulations of bipolar transistors may not predict correctly the measured electrical performance of shallow, heavily doped emitters and bases. This paper presents improved device physics for numerical simulations of solid-state devices with dopant densities up to about 3×10^{20} cm^{-3} and with junction depths as small as 0.1 μm. This improved device physics pertains to bandgap narrowing, effective intrinsic carrier concentrations, carrier mobilities, and lifetimes. When this improved device physics is incorporated into device analysis codes such as SEDAN and then used to compute the electrical performance of npn transistors, the predicted values agree very well with the measured values of the current-voltage characteristics and dc common-emitter gains for junction depths between 10 μm and 0.16 μm.
[(301) 921-3621]

Marchiando, J.F., Roitman, P., and Albers, J., **Verification of a Model for Boron Diffusion in Silicon**, IEEE Transactions on Electron Devices, Vol. ED-32, No. 11, pp. 2322-2330 (1985).

Understanding the effects of high- and low-temperature anneals of boron implanted in silicon is important in the calculation of shallow p-n junction profiles used as source and drain in p-channel MOSFETs. Here, a sample matrix of boron implanted into silicon over a range of fluences and annealing temperatures is considered. The matrix of samples was measured by SIMS (secondary ion mass spectrometry). The measured profiles were compared with simulations from an annealing/diffusion model. Calculations of the annealed profiles were found to be in agreement with the SIMS data at temperatures greater than 1000°C. At lower temperatures, the profiles exhibit effects due to implantation damage which are not included in the diffusion model.
[Contact: (301) 921-3621]

Roitman, P., Wilson, C.L., Blue, J.L.,

Process & Device Modeling, cont'd.

and Galloway, K.F., **Measurements for Accurate MOS Transistor Simulation,** Proceedings of the Third International Workshop on Physics of Semiconductor Devices, Delhi, India, November 27-December 2, 1985, pp. 69-77.

Measurements and input data required for accurate numerical simulation of MOS transistor characteristics are described. Techniques for determining dopant atom distributions, geometric parameters, and carrier mobility in the channel are discussed. The results are used to simulate the electrical characteristics of self-aligned, silicon-gate, n-channel MOSFETs with phosphorus source-drains having channel lengths of 0.80 μm, 1.83 μm, and 8.17 μm. It is possible to model the drain current for all of the transistors studied without adjustable parameters. If sufficiently accurate parameters are available, the characteristics of submicron transistors can be predicted with ±5% accuracy. [Contact: (301) 921-3621]

Wilson, C.L., **Using Silicon Device Modeling Techniques for GaAs Devices,** Technical Digest, 1985 International Electron Devices Meeting, Washington, D.C., December 1-4, 1985, pp. 78-81.

Numerical models have been developed for Si MOSFETs which achieve high accuracy and retain numerical stability and physical flexibility. The methods used in these models can be applied to GaAs MESFETs to yield a computer model which retains the accuracy and robust numerical properties of two-dimensional Si MOSFET models, yet retains most of the physical detail of Monte Carlo simulation. Two significant differences between this model and previous models result. First, by incorporating intraband scattering directly, high field regions of the device are seen to be dominated by alternate regions in which conduction by central valley and satellite valley electrons dominate. Second, the two-dimensional field shape in the part of the transistor between the gate and the drain is critical in calculating the intraband scattering and in determining the average effective mobility. [Contact: (301) 921-3621]

Wilson, C.L., and Blue, J.L., **Accurate Current Calculation in Two-Dimensional MOSFET Models,** IEEE Transactions on Electron Devices, Vol. ED-32, No. 10, pp. 2060-2068 (1985) [joint issue with IEEE Transactions on Computer-Aided Design, Vol. CAD-4, pp. 504-512 (1985)].

Two-dimensional simulations of MOSFETs are widely used for the design of short-channel transistors used in VLSI circuits. These models use low-order methods of discretization of solution variables. In this paper, a method of current calculation is presented which works with these methods and yields good accuracy. The method uses integration of the solution variables, rather than differentiation, and is similar to applying Ohm's law in two dimensions. [Contact: (301) 921-3621]

Wilson, C.L., Roitman, P., and Blue, J.L., **High Accuracy Physical Modeling of Submicron MOSFETs,** IEEE Transactions on Electron Devices, Vol. ED-32, No. 7, pp. 1246-1258 (1985).

Using the data obtained from the measurements described in this work, it is possible to model the drain current for all of the transistors studied with no adjustable parameters. Transistors with 0.81-μm channel length differ in model input from those with 8.17-μm channel length only in the length of the polysilicon gate. The accuracy of the simulation is maintained over the subthreshold, triode, and saturation regions and is comparable for all channel lengths. [Contact: (301) 921-3621]

Wilson, C.L., and Russell, T.J., **Two-Dimensional Modeling of Channel Hot-Electron Effects in Silicon MOSFETs,** Tech. Digest, 1985 International Electron Devices Meeting, Washington, D.C.,

Process & Device Modeling, cont'd.

December 1-4, 1985, pp. 72-75.

Earlier models have successfully modeled currents associated with device degradation due to channel hot-electrons. In this work, a high accuracy two-dimensional model of a silicon MOSFET is combined with a model of the SiO_2-Si interface which includes both the energy dependence of the interface traps within the silicon bandgap and the positional dependence of the oxide charge and the interface traps along the channel of the transistor. This model allows the effects of channel hot-electrons on the subthreshold, linear, and saturation region after injection of the device to be modeled without introducing free parameters.
[Contact: (301) 921-3621]

Witte, L.C., **CSFIT: A FORTRAN Program for Charge-Sheet Model Fitting of MOSFET Data**, NBSIR 85-3145 (November 1985).

A FORTRAN program, CSFIT, has been developed for fitting an expression for the current-voltage (I-V) characteristics of a long-channel MOSFET to experimental I-V curves. The one-dimensional charge-sheet model developed by Brews provides the basis for the I-V characteristics. The I-V characteristics given by this model are optimized with respect to a set of experimental data using the flatband voltage and the mobility as the only adjustable parameters. The program is written so that multiple sets of I-V data can be fit simultaneously if desired. The user must supply, in specified formats, a current-voltage data file, a device parameter file, and a starting value file.
[Contact: Charles L. Wilson (301) 921-3621]

Radiation Effects

Recently Published

Galloway, K.F., Wilson, C.L., and Witte, L.C., **Charge-Sheet Model Fitting to Extract Radiation-Induced Oxide and Interface Charge**, IEEE Transactions on Nuclear Science, Vol. NS-32, pp. 4461-4465 (1985).

A method for extracting values of oxide and interface charge from the current-voltage (I-V) characteristics of long-channel MOSFETs is described. The one-dimensional charge-sheet model developed by Brews provides the basis for the I-V characteristics. The I-V characteristics given by this model are optimized with respect to a set of experimental data for an irradiated device with the flatband voltage and the mobility the only free parameters. Simple relationships between these parameters and the radiation-induced interface and oxide charge are assumed.
[Contact: (301) 921-3541]

Galloway, K.F., Wilson, C.L., and Witte, L.C., **MOSFET Electrical Parameter Extraction from Charge-Sheet Model Fitting**, Proceedings of the Sixth Biennial University/Government/Industry Microelectronics Symposium, Auburn, Alabama, June 11-13, 1985, pp. 77-81.

A method for extracting the flatband voltage and the channel mobility from the current-voltage (I-V) characteristics of long-channel MOSFETs is described. The one-dimensional charge-sheet model developed by Brews provides the basis for the I-V characteristics. The I-V characteristics given by this model are optimized with respect to a set of experimental data with the flatband voltage and the mobility the only free parameters. A computer program, CSFIT, has been developed for this purpose. The choice of parameters is usually appropriate for a device subjected to a stress condition (e.g., hot-carrier injection or ionizing radiation). To illustrate the application of this method and CSFIT, the flatband voltage and mobility for an n-channel enhancement-mode device subjected to ionizing radia-

Radiation Effects, cont'd.

tion are determined from the I-V curves, and the changes of these parameters with radiation dose are tracked.
[Contact: (301) 921-3541]

Packaging

Recently Published

Oettinger, F.P., **Thermal Measurements of VLSI Packages - A Critical Overview**, Abstracts of the IEEE VLSI Packaging Workshop, Gaithersburg, Maryland, September 9-11, 1985, pp. 26-29.

Techniques to characterize thermally ceramic and plastic VLSI packages are discussed. Computer simulations and both direct and indirect thermal evaluation techniques are highlighted. Limitations and strengths of the various techniques are identified.
[Contact: (301) 921-3541]

Other Semiconductor Metrology Topics

Released for Publication

Zaghloul, M.E., **An Overview of Testability Measures in the Design of Digital Integrated Circuits.**

This paper is an overview of testability measures in the design of digital integrated circuits. Commercial testability algorithms are described and compared. Recent developments on testability measures which enhance the role of testability are discussed.
[Contact: Loren W. Linholm (301) 921-3801]

Recently Published

Stern, E.A., Ma, Y., and Bouldin, C.E., **The Local Structure at Mn Sites in Icosahedral Mn-Al Quasicrystals**, Physical Review Letters, Vol. 55, No. 20, pp. 2172-2175 (1985).

Extended x-ray absorption fine structure (EXAFS) measurements have been made at the Mn K-edge of quasicrystalline and crystalline forms of an Al_6Mn alloy. Two different quasicrystalline Mn sites are discerned to be populated in the ratio of τ within experimental error. The more populous site is similar to that in the crystal but with bond angle distortions and elimination of an unusually short Al-Mn bond, while the other site has additional bond stretching distortions. The EXAFS measurements together with density measurements indicate that the volume per Mn-site is independent of type of site, suggesting that the quasicrystal is not a Penrose lattice.
[Contact: Charles E. Bouldin (301) 921-3786]

FAST SIGNAL ACQUISITION, PROCESSING, & TRANSMISSION

Waveform Metrology

Recently Published

Bell, B.A., Editor, **Digital Methods in Waveform Metrology, Proceedings of a Seminar**, NBS Special Publication 707 (October 1985).

Modern electronic instrumentation metrology in the low-frequency regime (dc to 10 MHz) was discussed in lecture talks and papers presented at NBS, Gaithersburg, MD, on October 18-19, 1983. The seminar program was organized into four main session topics.

This special publication contains independent papers that enlarge on subjects presented at the seminar. Six papers represent and describe the hardware and software techniques used for developing NBS laboratory standards and apparatus for testing ac sources and voltmeters, phase angle meters, transient waveform recorders, wideband wattmeters, and digital-to-analog and analog-to-digital converters. Three papers have been written to supplement the informal session on Instrumentation Metrology and are included as Appendices.
[Contact: (301) 921-2727]

Waveform Metrology, cont'd.

Flach, D.R., **Characterization of Waveform Recorders,** Digital Methods in Waveform Metrology, Proceedings of a Seminar, NBS Special Publication 707, pp. 31-54 (October 1985).

Transient waveform recorders have been in use for more than 15 years with no commonly accepted test procedures for measuring the performance of these instruments in response to dynamic input signals. One test procedure that has been increasingly used by manufacturers and others in recent years involves the application of steady-state sinusoidal waveforms. These tests measure integral and differential linearity errors, missing codes, signal-to-noise ratios (effective number of bits), and aperture uncertainty.

Described are sine-wave tests that use non-linear, least-square curve fit procedures to measure the waveform recorder's noise, and thus the signal-to-noise ratio. This approach yields a "global" description of the recorder's errors. A sine-wave test in which the data are evaluated using a fast Fourier transform is described. This test is particularly useful to measure the integral linearity errors of the waveform recorder. A histogram test, which measures differential linearity errors and missing codes, is described. Results are given for the above tests. A method for measuring aperture uncertainty is briefly mentioned.

Two NBS-developed test procedures, a single-period transient sinusoidal test and a test based on the NBS voltage-step generator, are also described, and test results are given.
[Contact: (301) 921-2727]

Halford, D., **Transparency Metrology of Signal to Noise Ratios of Noisy Band-Limited Digital Signals,** NBS Tech. Note 1077 (June 1985).

I propose the use of a template method for quantitative, correct, and transparent measurement of signal power to additive noise power ratios (SNRs) of digital signals and systems under full operating conditions. Outer guard chips of digital templates hold intersymbol interference fixed on inner target chips in realizations of the respective template patterns in traffic. The proposed template method needs to be developed and proven as a potentially valuable metrology capability; it can be especially important for real-time on-line performance assessment and monitoring of digital communication systems.

A correct measurement procedure by definition actually measures a specified parameter of a specified signal, channel, device, or system. A transparent measurement procedure by definition measures the specified parameter without degradation of the usable channel capacity and without modification to or interference with the functioning of the measured system.

I discuss the significance of transparent metrology, the measurement of various SNRs by the template method, and the general applicability of the template method for measurements on any noisy digital signal. The template method can provide transparent metrology procedures for other basic measurands, e.g., intersymbol interference, multiplicative noises, and synchronization.
[Contact: (303) 497-5475]

Laug, O.B., **A Wide-Band Transconductance Amplifier for Current Calibrations,** IEEE Transactions on Instrumentation and Measurement, Vol. IM-34, No. 4, pp. 639-643 (December 1985).

A wide-band transconductance amplifier for current calibrations is described. The amplifier will deliver a ground-referenced constant current of 5 A rms from dc to over 100 kHz. Its stable magnitude and phase permit it to be used in precise power calibration systems to provide the current component of a phantom power source. The amplifier also

Waveform Metrology, cont'd.

provides a ground-referenced voltage output of 1 V/A for monitoring the magnitude and phase of the output current. [Contact: (301) 921-2727]

Laug, O.B., Stenbakken, G.N., and Leedy, T.F., **Electrical Performance Tests for Audio Distortion Analyzers,** NBSIR 85-3269 (November 1985).

Electrical performance test procedures for audio distortion analyzers were developed by the National Bureau of Standards for the U.S. Army Communications-Electronics Command. The report provides detailed, step-by-step test procedures that are based on specifications supplied by the Army for the purpose of evaluating audio distortion analyzer bid samples. Examples of data sheets and tables are also provided for recording interim and final results.

The report discusses the philosophy of each measurement procedure with a view toward providing an understanding of the basic metrology required to perform the measurements. In addition, the sources of measurement error are discussed. The primary applications and basic principles of modern audio distortion analyzers are also described.
[Contact: (301) 921-2727]

Major, J.R., Livingston, E.M., and Adair, R.T., **Automated Measurement of Frequency Response of Frequency-Modulated Generators, Using the Bessel Null Method,** Proceedings of the 4th Annual Test and Measurement World Expo, San Jose, California, May 14-16, 1985, pp. 78-100.

This paper describes a method for determining the frequency response of frequency-modulated generators, using a Bessel null method to control frequency deviation of the test signal applied to the generator. This test signal is in the form of a frequency-modulated radio-frequency carrier. A listing is provided of the computer program used in automating the method. The method applies to generators having an output frequency in the range 0.45 to 2000 MHz. Measurements obtained using this technique are more accurate than those obtained by a highly trained technician using a manual system.

Automated measurement of this process is desirable since the manual method is subject to the following problems: (1) excessive time, (2) error in finding the null, and (3) lack of assurance that the null is the first Bessel null. Automated measurements can be performed using a system controller, a spectrum analyzer, a function generator, and a voltmeter (all of which are compatible and controllable remotely).

The nonlinear relationship between modulating signal amplitude and the center frequency amplitude of the carrier is a major obstacle to automated measurement. This problem was solved by obtaining an approximate formula for this nonlinear curve.

Assurance that the null found is the first Bessel null is provided by the analysis of the frequency response of the test signal generator as displayed on the spectrum analyzer.
[Contact: (303) 497-3149]

Oldham, N.M., **Digital Waveform Synthesis Techniques,** Digital Methods in Waveform Metrology, Proceedings of a Seminar, NBS Special Publication 707, pp. 1-13 (October 1985).

The theory of digital waveform synthesis, including hardware implementations and practical limitations, is discussed. The generation of sinewaves as well as arbitrary waveforms using zero-order-hold and linear-point-connector reconstruction techniques is analyzed. An NBS-developed sinewave generator which provides a high-accuracy (50-ppm) signal from dc to 50 kHz is also described.
[Contact: (301) 921-2727]

Waveform Metrology, cont'd.

Schoenwetter, H.K., **A Programmable Precision Voltage-Step Generator for Testing Waveform Recorders,** IEEE Transactions on Instrumentation and Measurement, Vol. IM-33, No. 3, pp. 196-200 (September 1984).

A pulse generator for testing the approximate step-response of waveform recorders is described. The initial and final levels of voltage steps are each programmable within the range of ±1 V for a 50-Ω termination and within ±5 V for a high-impedance load. Voltage steps within these ranges settle to within ±0.02 percent of full-scale range in less than 30 and 40 ns, respectively, for a load capacitance of ≤30 pF. The corresponding 10- to 90-percent transition durations are approximately 7 and 12 ns.
[Contact: (301) 921-2727]

Schoenwetter, H.K., **Settling Time Measurements,** Digital Methods in Waveform Metrology, Proceedings of a Seminar, NBS Special Publication 707, pp. 87-109 (October 1985).

Methods are described for measuring the settling times (STs) and other dynamic characteristics of digital-to-analog converters, operational amplifiers, and precision voltage-step generators. The measurement of device STs from 5 μs to less than 20 ns with corresponding accuracies of 1 ppm and 0.1% is described.
[Contact: (301) 921-2727]

Souders, T.M., **Data Converter Test Methods,** Digital Methods in Waveform Metrology, Proceedings of a Seminar, NBS Special Publication 707, pp. 75-85 (October 1985).

Data converter test methods pertinent to measurement or control instrumentation applications are reviewed. Methods ranging from simple manual techniques to comprehensive fully automated approaches are discussed for both digital-to-analog and analog-to-digital converters. Strengths and weaknesses, major applications, and pertinent references are presented for each.
[Contact: (301) 921-2727]

Souders, T.M., and Stenbakken, G.N., **Modeling and Test Point Selection for Data Converter Testing,** Proceedings of the 1985 IEEE International Test Conference, Philadelphia, Pennsylvania, November 19-21, 1985, pp. 813-817.

Methods for generating efficient testing strategies for data converters are presented. Linear modeling techniques based on circuit analysis and empirical test data are included, as well as algorithms for selecting optimal test points. Using these tools, converter errors can be accurately estimated for all code states from a relatively small number of measurements.
[Contact: (301) 921-2727]

Stenbakken, G.N., **Dual-Channel Sampling Systems,** Digital Methods in Waveform Metrology, Proceedings of a Seminar, NBS Special Publication 707, pp. 55-73 (October 1985).

Measuring two signals simultaneously with a dual-channel sampling system allows for the calculation of many signal parameters not easily obtained with single-channel instruments. This paper concentrates on the use of dual-channel sampling for the measurement of power and phase angles. Theoretical interrelationships are developed for sampled data, measured quantities, and error sources. Both hardware and software errors are described. Calibration techniques are given for quantifying many of the error sources.
[Contact: (301) 921-2727]

Stenbakken, G.N., Souders, T.M., Lechner, J.A., and Boggs, P.T., **Efficient Calibration Strategies for Linear, Time Invariant Systems,** Proceedings Autotestcon '85, IEEE International Automatic Testing Conference, Uniondale, New York, October 22-24, 1985, pp.

Waveform Metrology, cont'd.

361-366.

An efficient strategy for accurately characterizing the frequency response of linear, time-invariant systems is presented. The approach, based on circuit modeling, test-point selection, and parameter estimation, optimizes calibration confidence with respect to test effort. The analytic tools and methodology needed for designing the strategy are included, together with experimental results. The approach can be particularly beneficial in volume testing of devices such as amplifiers, attenuators, and filters, or systems whose frequency response is dominated by such devices.
[Contact: (301) 921-2727]

Turgel, R.S., **Phase Angle Standards and Calibration Methods,** Digital Methods in Waveform Metrology, Proceedings of a Seminar, NBS Special Publication 707, pp. 15-29 (October 1985).

Measurement of phase angles in the audio frequency range is discussed with emphasis on precision phase meters and their calibration using an NBS-developed Phase Angle Calibration Standard.
[Contact: (301) 921-2727]

Turgel, R.S., **A Precision Phase Angle Calibration Standard for Frequencies up to 50 kHz,** IEEE Transactions on Instrumentation and Measurement, Vol. IM-34, No. 4, pp. 509-516 (December 1985).

A phase angle calibration standard covering a frequency range from 2 Hz to 50 kHz has been designed and constructed. Digital waveform generation is used to provide sinusoidal analog outputs having precisely settable phase angles. Output voltages are independently adjustable from 0.5 to 100 V rms on both channels. An auto-zero feed-back loop compensates for differential phase errors of the output amplifiers.
[Contact: (301) 921-2727]

Cryoelectronic Metrology

Recently Published

Niemeyer, J., Hinken, J.H., and Kautz, R.L., **Near-Zero Bias Arrays of Josephson Tunnel Junctions Providing Standard Voltages Up to 1 V,** IEEE Transactions on Instrumentation and Measurement, Vol. IM-34, No. 2, pp. 185-187 (June 1985).

Josephson voltage standards utilize microwave-induced constant voltage steps occurring due to the ac Josephson effect. Existing standards can be considerably simplified and their accuracy improved by using a large number of series-connected Josephson tunnel junctions which are operated in the zero-current-step mode. For this purpose, superconducting millimeter wave integrated circuits have been designed, fabricated, and tested. The circuits consist of a broadband taper between the rectangular waveguide and the planar structure, the Josephson junction series, a well-matched load, and dc pads. Circuits with various numbers of junctions have been fabricated by photolithographic techniques and tested at 4.2 K in liquid helium. The version with 1474 junctions produced voltages up to 1.2 V when operated at 90 GHz.
[Contact: Richard L. Kautz, (303) 497-3391 or -3988]

Antenna Metrology

Released for Publication

Lewis, R.L., and Newell, A.C., **An Efficient and Accurate Method for Calculating and Representing Power Density in the Near-Zone of Microwave Antennas,** to be published as NBSIR 85-3036.

An algorithm is presented for calculating near-zone and Fresnel-region fields in front of microwave antennas from discrete numerical values of the

Antenna Metrology, cont'd.

radiated plane-wave spectrum (complex far-field pattern). That is, the near fields are calculated by numerically integrating the plane-wave spectrum representation of the field. The crux of the analysis consists of handling a numerical instability which arises from integrating discrete data. A criterion is developed for limiting the integration domain in order to exclude highly oscillatory regions of the integrand. In turn, this leads to restricting the applicable output range over which the field can be computed. With the numerical instability problem thus resolved, fast Fourier transform techniques are used to assure efficient numerical integration over a large (but restricted) output range. The results are conveniently presented as relative power-density contours in planes formed by the longitudinal coordinate axis and one transverse coordinate axis. The algorithm is capable of extremely high accuracy, which is demonstrated by comparing predicted and measured near-fields for two distinct antennas, along with a comparison against an exact theoretical model. In the case of circularly symmetric excitation models for electrically large antenna apertures, the predicted relative near-zone power-density contour plots turn out to be a function of only the relative aperture distribution. Nomographs for obtaining absolute near-zone power densities are presented for a few typical aperture-distribution functions.
[Contact: (303) 497-5196]

Muth, L.A., **Interelement Interactions in Phased Arrays: Theory, Methods of Data Analysis, and Theoretical Simulations,** to be published as NBS Tech. Note 1090.

We review theoretically the effects of multiple reflections and mutual impedances in array environments, and study possible methods of far-field pattern data analysis to recover interaction effects. We use theoretical expressions derived earlier to calculate in a two-element linear array the mutual impedance matrix.
[Contact: (301) 921-3603]

Recently Published

Jesch, R.L., **Measured Vehicular Antenna Performance,** IEEE Transactions on Vehicular Technology, Vol. VT-34, No. 2, pp. 97-107 (May 1985).

Power gain radiation patterns of mobile antennas mounted in six different locations on a test vehicle were measured with and without typical lights and sirens mounted on the roof. The measurements were performed at frequencies representing the frequency bands of 25 to 50, 150 to 174, 400 to 512, and 806 to 866 MHz. In addition, special antennas consisting of three disguised antennas operating at discrete frequencies of 40.27, 162.475, and 416.975 MHz and one slot antenna operating at 413 MHz were also measured. Plots of power gain radiation patterns are given for the mobile antennas mounted in six different locations on the test vehicle and for the special antennas. Results showing the effects of poor grounding characteristics are also included. Recommended locations for mounting the mobile antennas are given for specific frequency bands.
[Contact: (303) 497-3496]

Muth, L., **A Theory of Mutual Impedances and Multiple Reflections in an N-Element Array Environment,** Proceedings of the 1985 International Symposium on Antennas and Propagation, Kyoto, Japan, August 20-22, 1985, pp. 719-722, and Proceedings of 1985 International Symposium on Antennas and EM Theory, Beijing, China, August 26-28, 1985, pp. 440-447 [these papers are shortened versions of NBS Tech. Note 1078 published in February 1985].

A general theoretical approach is formulated to describe the complex electromagnetic environment of an N-element

Antenna Metrology, cont'd.

array. The theory reveals the element-to-element interactions and multiple reflections within the array. From the formulation, it is found that the interaction between an excited element and an open-circuited element can be viewed as the sum of terms describing all possible signal paths within the array environment which start from the radiating element and terminate on the element under observation. Within all paths except the most direct one, multiple reflections between subgroups of elements take place. The resulting solution is highly structured and recursive and is discussed in detail in the text. Illustrative examples are provided to facilitate understanding of these ideas.
[Contact: (303) 497-3603]

Newell, A.C., Francis, M.H., Kremer, D.P., and Grimm, K.R., **Results of Planar Near Field Testing with Ultralow Sidelobe Antennas**, Symposium Digest of the IEEE/AP-S International Symposium 1985, Antennas and Propagation, Vancouver, B.C., June 17-21, 1985, pp. 693-698.

An investigation to demonstrate Planar Near Field measurement accuracy for ultralow sidelobe antennas is nearing completion at the National Bureau of Standards, Boulder, Colorado. The existing NBS scanner has been modified to accommodate antennas up to 10 m long and 4 m high. Two antennas will be measured as part of this research effort. They are the AWACS (U.S. Airborne Warning and Control System) and the ULSA (Ultra Low Sidelobe Antenna) travelling wave antennas which are, respectively, 8 m × 1.5 m and 6 m × 1 m. Results of tests to introduce controlled near-field measurement error confirm predicted far-field sidelobe accuracies at the ~60-dB level. Additional results show the utility of a new two-element probe to extend sidelobe measurement accuracy by steering a probe pattern null in the direction of the test antenna's mainbeam.
[Contact: (303) 497-3743]

Newell, A.C., and Repjar, A.G., **Development of Near-Field Test Procedures for Communication Satellite Antennas, Phase I, Part 1**, NBSIR 85-3031 (September 1985).

The purpose of this program is to define and further develop the capabilities of near-field antenna test techniques, specifically for the requirements associated with the development and verification testing of reconfigurable, multibeam, frequency reuse, commercial satellite antennas. Phase I, Part 1 gives a general survey, definition, and description of near-field and compact range measurement methods as they apply to satellite antenna systems testing. Each of these methods is evaluated to determine how well they meet the measurement requirements. Included for each technique is a summary of the measurement method, discussions on probe correction and data processing, measurement hardware considerations, a results-available section, and measurement accuracy and range certification considerations. The basis for the choice of the best measurement technique is established with the planar near-field measurement method receiving the best score for the directive antennas considered. As a result, further study will focus on this technique and will be reported on subsequently. A detailed presentation of planar near-field measurements theory is presented in Appendix A.
[Contact: (303) 497-3743]

Microwave Metrology

Released for Publication

Engen, G.F., **An Introduction to the Six-Port Automatic Network Analyzer**, to be published in the Conference Digest, Test & Measurement World Expo, San Jose, California, April 8-10, 1986.

The "six-port" differs from other auto-

Microwave Metrology, cont'd.

matic network analyzers in its use of simple amplitude detectors as contrasted with heterodyne methods. This paper presents an elementary introduction to the subject and outlines some of the advantages and limitations of the method.
[Contact: (303) 497-3511]

Weidman, M., **Finline Diode Six-Port Fundamentals and Design Information**, to be published as NBS Tech. Note 1090.

The preliminary design and testing of a planar circuit six-port with diode detectors is described. The planar circuit medium was chosen to be finline, and all preliminary work was done in WR-42 waveguide (18 to 26.5 GHz). The finline substrate was alumina, and initially commercial beam-lead diodes were bonded to the finline metallization. The goal is to design an integrated circuit which could be fabricated on one chip (with diode detectors) and used as part of a six-port network analyzer in the waveguide bands above 18 GHz. Initial designs proved to be unsatisfactory because of high losses and reflections. Most of the problems have been solved, and a usable integrated finline circuit is a good possibility for a millimeter wave six-port.
[Contact: (303) 497-3210]

Recently Published

Wilson, P.F., and Chang, D.C., **Mode Coupling by a Longitudinal Slot for a Class of Planar Waveguiding Structures: Part I - Theory**, also **Part II - Applications**, IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-33, No. 10, pp. 981-993 (October 1985).

Coupling between two parallel-plate waveguides is investigated. Mutual excitation is due to a longitudinal slot in a common plate. The introduction of reflecting boundaries parallel to the slot allows one to model a number of planar waveguiding structures featuring a common coupling mechanism. Part I of this paper details the analysis of the basic slot scattering problem based on the singular integral equation method. If one assumes that the slot is small, then closed-form algebraic modal equations follow. These modal equations are well adapted to numerical parametric studies.

Part II of this paper presents specific examples of the above approach along with numerical results. Examples include a rectangular coaxial transmission line, broadwall-coupled rectangular waveguides, coupled microstrips, and coupled microstrip and rectangular waveguide.
[Contact: (303) 497-3842]

Laser Metrology

Released for Publication

Rasmussen, A.L., and Franzen, D.L., **Low Level Germanium Detector Transfer Standard at 1.064 μm**, to be published as NBSIR 85-3041.

Two PIN germanium photodiodes have been calibrated in the 1- to 250-fJ/cm^2 range with 15 percent uncertainty for 10- to 100-ns durations, 1.064-μm laser pulses. To do these calibrations, we used (1) a cw Nd:YAG laser beam acousto-optically modulated and a PIN silicon photodiode transfer standard to provide low-level laser pulses of known energy and (2) a pulsed 1.06-μm LED beam. A 1-cm^2 collecting lens and a ground glass diffuser were placed in front of each detector to improve sensitivity and spatial uniformity, respectively. In the future, these detectors may also be useful as transfer standards at wavelengths out to 1.7 μm.
[Contact: (303) 497-5367 or -3616]

Recently Published

Johnson, E.G., **Direct Measurement of the Spatial Modes of a Laser Pulse --**

Laser Metrology, cont'd.

Theory, NBS Tech. Note 1084 (August 1985).

We consider realizing an electric-field measuring apparatus to measure the temporal and spatial modes of a laser pulse by using optical processing, tapered optical fibers, and a pair of detectors at the end of each optical fiber. Using an appropriate computer-generated hologram (CGH), we show it is possible to discriminate among a set of orthonormal modes used to represent the spatial features of the electric field with a signal-to-noise ratio of at least 100 to 1. The tapered fiber is a mode filter that is used in the transform plane of the CGH. This fiber allows the precise determination of the strength of each of the orthonormal modes being used as the spatial basis of the electric field before the optical processing.
[Contact: (303) 497-3234]

Rasmussen, A.L., and Sanders, A.A., **Documentation of the NBS APD and PIN Calibration Systems for Measuring Peak Power and Energy of Low-Level 1.064 μm Laser Pulses,** NBSIR 85-3032 (December 1985).

National Bureau of Standards APD (Avalanche) and PIN silicon photodiode transfer standards are documented for a calibration service to measure 1.064-μm laser pulses from $\sim 10^{-8}$ to $\sim 10^{-4}$ W peak power and $\sim 10^{-16}$ to $\sim 10^{-11}$ J energy. A modulated continuous-wave measurement system generating known low-level pulse is described. Calibration support equipment, systematic and random errors, and computer programs and calibration data are also described.
[Contact: (303) 497-5367 or -3616]

Optical Fiber Metrology

Released for Publication

Day, G.W., McFadden, J.D.O., Veeser, L.R., Chandler, G.I., and Cernosek, R.W., **Optical Fiber Sensors for the Measurement of Pulsed Electric Currents,** to be published in the Proceedings of the AGARD (NATO Advisory Group for Aerospace Research and Development) Specialists Meeting on Optical Guided Waves in the Military Environment, Istanbul, Turkey, September 23-27, 1985.

Recent progress in the design of fiber sensors for pulsed electric currents is reviewed. Several of the most useful sensor configurations are described and compared. Models are used to predict the transfer function of these sensors, their sensitivity to nonideal fiber properties, particularly linear birefringence, and methods for overcoming these problems. Other recent research is examined to suggest the prospect for sensors with improved sensitivity and stability.
[Contact: (303) 497-5204]

Franzen, D.L., **Standard Measurement Procedures for Characterizing Single-Mode Fiber,** to be published in the Conference Digest, Test & Measurement World Expo, San Jose, California, April 8-10, 1986.

Parameters used to describe single-mode fiber include attenuation, cut-off wavelength, mode-field diameter, and dispersion. Results for some measurements depend on the condition of the test fiber and the method used. This paper describes the latest recommendations from standards groups and gives typical examples of achieved measurement precision.
[Contact: (303) 497-3346 or -5342]

Gallawa, R.L., and Shao, Y., **Optical Power Meters: A Round Robin Test on Precision.**

The proliferation of optical fiber systems has spawned the introduction of a variety of optical power meters. These meters are crucial to the analysis and maintenance of fiber communciation systems. In this paper we give the results

Optical Fiber Metrology, cont'd.

of an interlaboratory experiment to determine the precision of the meters being used in the fiber community. The results indicate that the precision of power meter readings in different laboratories is not good. The precision improved when measurements taken with very small-area detectors were excluded.
[Contact: (303) 497-3761]

Kanada, T., and Franzen, D., **Single-Mode Fiber Dispersion Measurements Using Optical Sampling with a Modelocked Laser Diode.**

Pulses from a wavelength-tunable, modelocked laser diode are measured after 21 km of single-mode fiber propagation by optical sampling with another modelocked laser diode; a resolution of 0.1 ps/nm•km is achieved in this chromatic dispersion measurement. In another related experiment, 78-ps duration pulses from an ordinary, multilongitudinal mode laser diode are clearly displayed by optical sampling after 36 km of fiber propagation. System bandwidth increases to approximately 500 GHz•km as the laser diode wavelength is temperature tuned through the zero dispersion region.
[Contact: Douglas L. Franzen (303) 497-3346 or -5342]

Other Fast Signal Topics

Released for Publication

Bell, B.A., and Perrey, A.G., **Evaluation of Electronic Monitoring Devices,** to be published as a National Institute of Justice Report.

Two electronic systems used for monitoring the location of persons sentenced to home confinement were tested to determine their operating frequency, approximate range of operation, component compatibility, tamper resistance, and other characteristics such as safety. Tests were conducted in an open field, in a wooden residence, in a high-rise building, and in a laboratory environment.
[Contact: (301) 921-2727]

Hill, D.A., and Wait, J.R., **Anomalous Vertical Magnetic Field for Electromagnetic Induction in a Laterally Varying Thin Conductive Sheet.**

We employ a simple model to show how the natural electromagnetic field on the surface of the earth, which has a strong horizontal magnetic field component, can be converted to a significant vertical magnetic field at the surface. Such a conversion mechanism will be caused by lateral variations of the subsurface conductivity structure. Our idealized model is a thin conducting sheet with a periodic variation of the conductivity-thickness product in one horizontal direction only.
[Contact: (303) 497-3472]

Recently Published

Bensema, W.D., **Personal RM Transceivers,** NIJ Standard 0209.01, National Institute of Justice, Technology Assessment Program (September 1985).

This document is an equipment standard developed by the Law Enforcement Standards Laboratory of the National Bureau of Standards and is produced as part of the Technology Assessment Program of the National Institute of Justice. The standard specifies performance and other requirements equipment should meet to satisfy the needs of criminal justice agencies for high-quality service. Performance requirements and methods of test are presented for nontrunked frequency modulated (FM) personal transceivers and their associated antennas and power sources. The standard applies to transceivers which either do not have special subsystems such as selective signaling or voice privacy, or in which such subsystems are bypassed or disabled during testing for compliance with the standard.
[Contact: (303) 497-3465]

Other Fast Signal Topics, cont'd.

Daywitt, W.C., **Complex Permittivity of Beryllium Oxide Between 100 and 300 K at 9.3 GHz**, IEEE Transactions on Instrumentation and Measurement, Vol. IM-34, No. (1), pp. 98-99 (1985).

9.3 GHz measurement results of the relative permittivity and loss tangent of beryllium oxide at 99, 145, 223, and 300 K are reported.
[Contact: (303) 497-3720]

Hill, D.A., **Radio Propagation in a Coal Seam and the Inverse Problem,** Proceedings of the 1985 International Symposium on Antennas and EM Theory, Beijing, China, August 26-28, 1985, pp. 422-427.

The longwall method of coal mining in underground coal seams is very efficient in uniform seams, but coal seam anomalies can make the method unprofitable and unsafe. This paper describes the theoretical basis for detection of coal seam anomalies using medium frequency radio transmission over paths on the order of 200 meters in length. The key to the method is the sensitivity of the attenuation rate of the coal seam mode of propagation to changes in the coal seam parameters, such as height or electrical conductivity. From a large number of transmission paths, the principles of tomography can be used to reconstruct an image of the seam.
[Contact: (303) 497-3472]

Young, M., **The Scratch Standard Is Only a Cosmetic Standard,** Laser Focus/Electro-Optics, pp. 138-140 (November 1985). [An identical paper appeared in the Proceedings of the Conference on Laser Induced Damage in Optical Materials, Boulder, Colorado, October 28-30, 1985.]

A history of the scratch and dig standard is presented, describing its application and pointing out that it may not be used for quantitative assessments such as width measurement.
[Contact: (303) 497-3223 or -5342]

ELECTRICAL SYSTEMS

Power Systems Metrology

Released for Publication

Petersons, O., and Mehta, S.P., **Calibration of Test Systems for Measuring Power Losses of Transformers,** to be published as NBS Technical Note 1204.

A calibration system for accuracy verification and alignment of test systems for measuring transformer losses is described. Methodologies are presented for assessing measurement uncertainties and for evaluating overall accuracy of test systems. Procedures are suggested for continuing maintenance and calibration of standard instruments and test systems to ensure traceable measurements.
[Contact: (301) 921-2328]

Recently Published

Oldham, N.M., **Power Calibration Standard Based on Digitally Synthesized Sinewaves,** IEEE Transactions on Power Apparatus Systems, Vol. PAS-104, No. 11, pp. 3117-3121 (November 1985).

The unit of electric power at 60 Hz is often derived using impedance bridge techniques in which the alternating voltage is referred to the direct voltage standard through a thermal converter. An alternative calibration technique is described in which the ac-to-dc transfer is made through digital-to-analog converters (DACs) in the form of a dual-channel digital sinewave generator. The power is calculated from measurements of voltage, current, and phase angle, all of which rely on the accuracy of the digital generator and ultimately on the accuracy of the DACs. Measurement uncertainties of less than 100 ppm have been achieved.
[Contact: (301) 921-2727]

Oldham, N.M., and Petersons, O., **Cali-**

Power Systems Metrology, cont'd.

bration of Standard Wattmeters Using a Capacitance Bridge and a Digital Generator, IEEE Transactions on Instrumentation and Measurement, Vol. IM-34, No. 4, pp. 521-524 (December 1985).

A method for calibrating high-accuracy wattmeters is described. The technique is a modification of a previously described approach that utilizes a power bridge based on a current comparator. In such a bridge, the test current of the wattmeter is balanced with a known current that is proportional to the test voltage. The measurement circuit described employs a high-voltage capacitance bridge in place of a special current comparator that was used in the previous system. High sensitivity and large ratios of the capacitance bridge enable using high impedances, such as stable gas-dielectric capacitors and resistors having low-power dissipation for the generation of reference currents. The voltage on the standard impedances is adjusted with inductive dividers to obtain any power factor between zero and one, lead and lag. A digitially synthesized dual-channel signal source serves as a stable source of voltage and current, and thus of "phantom" power.
[Contact: (301) 921-2727]

Pulse Power Metrology

Released for Publication

Hebner, R.E., **High-Speed Data Systems for Pulsed Power Applications,** to be published in the Proceedings of the 5th IEEE Pulsed Power Conference, Arlington, Virginia, June 10-12, 1985.

Data-acquisition systems for pulsed power applications generally must provide nanosecond resolution, operate in an environment of high levels of electromagnetic interference, and acquire significant amounts of data simultaneously. To meet these demands, electrical systems have been used and optical systems are being introduced. Voluntary standards have been and are being developed which categorize the errors in the electrical measurement systems. Optical systems are in too early a state of development for similar standardization.
[Contact: (301) 921-3121]

Superconductors

Released for Publication

Dube, W.P., and Goodrich, L.F., **A Quench Detector Design for Superconductor Testing.**

A quench detector is a device that interrupts the flow of current through a superconductor in the event the superconductor reverts to the normal, resistive state. This new design has adjustable filtering and sensitivity. The input is well isolated from the output, eliminating any possible ground loop through the detector. It also has excellent noise immunity.
[Contact: Loren F. Goodrich (303) 497-3143]

Ekin, J.W., **High-Field Flux Pinning and the Strain Scaling Law,** to be published in the Proceedings of the International Symposium on Flux Pinning and Electromagnetic Properties in Superconductors, Fukuoka, Japan, November 11-15, 1985.

The effects of strain on flux pinning in superconductors are discussed. Significant differences between the strain scaling law, temperature scaling law, and the flux-line-shearing model of Kramer are demonstrated. The strain scaling law is more general than current flux-pinning models, and as such, it may serve as a guide to future work on flux pinning theory. Flux-pinning measurements at fields up to 24 T have been made on a series of high-quality Nb_3Sn samples with third (and fourth) element additions. The data show that the usual extrapolation procedures for determining the bulk-average upper critical field in Nb3Sn lead to significant errors when

Superconductors, cont'd.

additives such as Ti, Ta, Ga, and Hf are present.
[Contact: (303) 497-5448]

Recently Published

Moreland, J., and Ekin, J.W., **Electron Tunneling Experiments Using Nb-Sn "Break" Junctions**, Journal of Applied Physics, Vol. 58, No. 10, pp. 3888-3895 (15 November 1985).

An Nb-Sn filament mounted on a flexible glass beam can be broken to form an electron tunneling junction between the fracture elements. Breaking the filament in liquid helium prevents oxidation of the freshly exposed fracture surfaces. A sharp superconducting energy gap in the I-V characteristics measured at 4 K indicates the formation of a high-quality tunneling barrier between the fracture elements. The resistance of the junction between the fracture elements can be continuously adjusted by varying the surface-bending strain of the beam. An estimated 0.1-nm change in the barrier thickness produces about an order of magnitude change in the resistance over the range from 10^5 to 10^8 Ω. The exponential character of this dependence shows that the tunnel junction is freely adjustable without intimate contact of the junction elements. "Break" junctions made in this way offer a new class of tunneling experiments on freshly exposed surfaces of a fractured sample without the oxide barrier previously required for junction stability. Such experiments provide a simple technique for tunneling to new materials and may eliminate complications that can be encountered during interpretation of data obtained using oxide barriers.
[Contact: (303) 497-3641]

Moreland, J., and Ekin, J.W., **Electron Tunneling into Superconducting Filaments Using Mechanically Adjustable Barriers,** Applied Physics Letters, Vol. 47, No. 2, pp. 175-177 (15 July 1985).

A new type of squeezable electron tunneling (SET) junction has been developed for tunneling into superconducting filaments. Stable, mechanically adjustable tunneling barriers between the native surfaces of sputtered Nb films and 30-μm diameter Nb filaments were established in liquid helium at 4 K. The current-versus-voltage characteristics of these SET junctions were used to determine the superconducting energy gap at the surface of the filaments. Since the filameters were etched from commercial superconducting magnet wire, this type of tunnel junction shows promise as a diagnostic probe of superconducting materials for high-field magnets.
[Contact: (303) 497-3641]

Magnetic Materials and Measurements

Released for Publication

Capobianco, T.E., **A Review of Eddy Current Research at the National Bureau of Standards in Boulder, Colorado,** to be published in the Proceedings of the DoD Conference on Nondestructive Evaluation, Charleston, South Carolina, October 29-31, 1985.

On-going research in eddy current nondestructive evaluation at the National Bureau of Standards in Boulder, Colorado, is reviewed. The most recent results and publications of experimental and theoretical studies are presented. This includes the areas of eddy current coil characterization and field mapping, experimental verification of eddy current-fatigue crack interaction, uniform field probe calibration, artifact standards, fatigue crack growth monitoring, and differential eddy current probe studies.
[Contact: (303) 497-3141]

ELECTROMAGNETIC INTERFERENCE

Released for Publication

Adams, J.W., and Vanzura, E., **Shielding Effectiveness Measurements of Plastics,** to be published as NBSIR 85-

Electromagnetic Interference, cont'd.

3035.

Measurement of shielding effectiveness of plastic materials with respect to electromagnetic radiation poses serious problems due to the insulating nature of many plastics. A method of making these measurements using a flanged coaxial holder overcomes some of the difficulties.
[Contact: (303) 497-3328]

Crawford, M.L., and Koepke, G.H., **Design, Evaluation, and Use of a Reverberation Chamber for Performing Electromagnetic Susceptibility/Vulnerability Measurements**, to be published as NBS Tech. Note 1092.

This report presents the results of work at the National Bureau of Standards, Boulder, Colorado, to carefully evaluate, document, develop (when necessary), and describe the methodology for performing radiated susceptibility/vulnerability measurements using a reverberation chamber. The report describes the reverberation chamber theory of operation, construction, evaluation, functional operation, and use for performing immunity measurements. It includes an estimate of measurement uncertainties derived empirically from test results and from comparisons with anechoic chamber measurements. Finally, it discusses the limitations and advantages of the measurement technique to assist potential users in determining the applicability for this technique to their electromagnetic compatibility (EMC) measurement needs.
[Contact: (303) 497-5497]

Friday, D.S., **Methodology for Statistical Control of the Anechoic Chamber Field Generation System,** to be published as NBSIR 85-3033.

The microwave anechoic chamber is an NBS laboratory facility in which standard plane-wave electromagnetic fields are generated. The chamber enables specialized measurements and electromagnetic interference/electromagnetic compatibility tests to be conducted on antennas and other devices. This paper is concerned with methodology for assuring that the standard field patterns generated in the chamber are repeatable. Procedures are proposed for developing a data base from measurements obtained by placing the system, which generates the fields, in certain relevant reference configurations. Methodology is presented for developing statistical control charts to monitor both the location and the scale parameters of these data over time.
[Contact: (303) 497-5395]

Hill, D.A., **An Error Bound for Near-Field Array Synthesis.**

An expression for the upper bound of any component of the electric or magnetic field at any point in a region is derived in terms of a product of two surface field integrals. The result is most helpful for bounding errors in near-field array synthesis, but might have other applications where upper bounds on field magnitudes are desired.
[Contact: (303) 497-3472]

Hill, D.A., **Out-of-Band Response of a Coax-to-Waveguide Adapter.**

The input impedance and transmission coefficients of a coax-to-waveguide adapter are analyzed for out-of-band frequencies. Numerical results are shown for an S-band adapter for frequencies from 2 to 10 GHz. The above-band response is frequency sensitive because of the presence of higher-order propagating modes in the waveguide.
[Contact: (303) 497-3472]

Hill, D.A., and Wait, J.R., **Anomalous Vertical Magnetic Field for Electromagnetic Induction in a Laterally Varying Thin Conductive Sheet.**

We employ a simple model to show how the natural electromagnetic field on the surface of the earth, which has a strong

Electromagnetic Interference, cont'd.

horizontal magnetic field component, can be converted to a significant vertical magnetic field at the surface. Such a conversion mechanism will be caused by lateral variations of the subsurface conductivity structure. Our idealized model is a thin conducting sheet with a periodic variation of the conductivity-thickness product in one horizontal direction only.
[Contact: (303) 497-3472]

Phelan, R.J., Jr., Larson, D.R., and Simpson, P.A., **A Sensitive, High Frequency, Electromagnetic Field Probe Using a Semiconductor Laser in a Small Loop Antenna**, to be published in Proc. SPIE - The International Society for Optical Engineering, Vol. 559 [Conference, San Diego, California, August 18-23, 1985].

Using a loop antenna in series with a semiconductor laser, an optically coupled electromagnetic field probe has demonstrated sensitivities better than 1 $\mu V/m/Hz^{1/2}$. The probe outside dimensions are equal to $5.7 \times 5.7 \times 1.3$ cm^3. It can be used to measure frequencies as high as 2 GHz. The dynamic range is estimated to exceed 6 orders of magnitude for incident microwave powers.
[Contact: (303) 497-3696 or -5342]

Recently Published

Crawford, M.L., and Koepke, G.H., **Comparing EM Susceptibility Measurement Results Between Reverberation and Anechoic Chambers**, Proceedings of the 1985 IEEE International Symposium on Electromagnetic Compatibility, Wakefield, Massachusetts, August 20-22, 1985, pp. 152-160.

This paper compares measurement results obtained using a (2.7 × 3.1 × 4.6)-m reverberation chamber and a (4.9 × 6.7 × 8.5)-m anechoic chamber to determine the electromagnetic susceptibility of equipment under test (EUT). The frequency range is 200 MHZ to 18 GHz. The "correlation factor" between the two techniques appears to be directly proportional to the gain of the EUT. Four sample EUTs included in this study were a 1-cm dipole probe, a ridged horn antenna, a small rectangular TEM transmission cell with an aperture, and a modified 7.0 cm (2.75") diameter folded-fin aircraft rocket.
[Contact: (303) 497-5497]

Cruz, J.E., Driver, L.D., and Kanda, M., **Design of the National Bureau of Standards Isotropic Magnetic Field Meter (MFM-10) 300 kHz to 100 MHz**, NBS Tech. Note 1085 (October 1985).

A broadband magnetic field meter has been developed at the National Bureau of Standards (NBS) for the frequency range of 300 kHz to 100 MHz. The isotropic antenna unit consists of three mutually orthogonal loops, each 10 cm in diameter. The magnetic field probe described in this paper has a measurement range of 0.1 to 30 A/m. The readout of the meter is in terms of the Hermitian or "total" magnitude of the magnetic field strength which is equal to the root-sum-square value of the three orthogonal magnetic field components at the measurement point. This magnetic field meter is nearly isotropic over its dynamic range.

The electronic circuitry of the meter obtains the total magnitude of all field polarizations for all cw signals in the entire frequency band. The sensor is isotropic and is well suited for measuring the near field of an emitter, including regions of multiple reflections and standing waves. The meter can be used to monitor either the plane wave fields in the far zone of a transmitter, or the complicated fields very close to a radiofrequency leakage source. This report describes the design, performance, and operating instructions for the MFM-10.
[Contact: (303) 497-3763]

FitzGerrell, R.G., **Site Attenuation**, NBS Tech. Note 1089 (November 1985) [a

Electromagnetic Interference, cont'd.

shortened version of this paper appeared in the Proceedings of the IEEE 1985 International Symposium on Electromagnetic Compatibility, Wakefield, Massachusetts, August 20-22, 1985].

Site attenuation is a measure of performance of an open test site at frequencies below about 1 GHz. These sites typically consist of a large, obstruction-free ground plane and the hemisphere above it. Calculations of site attenuation are presented which provide a reference for measurements made on a 30-m by 60-m wire-mesh ground screen. Measured data are compared to the calculated results.
[Contact: (303) 497-3737]

Hill, D.A., and Koepke, G.H., **An Array of Dipoles for Plane Wave Synthesis,** Proceedings of the 1985 International Symposium on Antennas and Propagation, Kyoto, Japan, August 20-22, 1985, pp. 177-180.

Phased arrays can be used to produce a nearly uniform plane wave in the near field. This paper describes a small array of dipoles which we have studied theoretically and experimentally. The element excitations are determined from a near-field synthesis technique that optimizes the field uniformity throughout the test volume.
[Contact: (303) 497-3472]

Jesch, R.L., **Measured Vehicular Antenna Performance,** IEEE Transactions on Vehicular Technology, Vol. VT-34, No. 2, pp. 97-107 (May 1985).

Power gain radiation patterns of mobile antennas mounted in six different locations on a test vehicle were measured with and without typical lights and sirens mounted on the roof. The measurements were performed at frequencies representing the frequency bands of 25 to 50, 150 to 174, 400 to 512, and 806 to 866 MHz. In addition, special antennas consisting of three disguised antennas operating at discrete frequencies of 40.27, 162.475, and 416.975 MHz and one slot antenna operating at 413 MHz were also measured. Plots of power gain radiation patterns are given for the mobile antennas mounted in six different locations on the test vehicle and for the special antennas. Results showing the effects of poor grounding characteristics are also included. Recommended locations for mounting the mobile antennas are given for specific frequency bands.
[Contact: (303) 497-3496]

Kanda, M., **A Methodology for Evaluating Microwave Anechoic Chamber Measurements,** Proceedings of the 6th Symposium and Technical Exhibition on Electromagnetic Compatibility, Zurich, Switzerland, March 5-7, 1985, pp. 69-74.

This paper discusses a methodology for evaluating anechoic chamber measurements. Anechoic chamber measurement is evaluated in terms of the net power delivered to a transmitting antenna, the near-zone gains of open-ended rectangular waveguides and rectangular pyramidal horns, and reflections from chamber walls. The on-axis field intensity of the standard transmitting horn in an anechoic chamber is calculated in terms of the net power delivered to the transmitting antenna. The resulting data can be used for estimating the overall uncertainty in the anechoic chamber measurements. Statistical control of the measurement process by use of transfer standard antennas will monitor the measurement uncertainties.
[Contact: (303) 497-5320]

Randa, J., and Kanda, M., **Directional Scanning of Complex Electromagnetic Environments,** Proceedings of the 1985 International Symposium on Antennas and Propagation, Kyoto, Japan, August 20-22, 1985, pp. 899-902.

As radiofrequency and microwave sources (both intentional and inadvertent) multiply, the electromagnetic (EM) environ-

Electromagnetic Interference, cont'd.

ment in which electronic devices (and people) must function becomes increasingly complicated, while at the same time its characterization becomes more important. In order to completely characterize an EM environment without knowledge of the radiating sources, the sampling theorem requires that systematic measurements of the amplitude and phase of the field be made throughout the volume at spacings of no more than one-half wavelength (of the highest frequency present). This is often impossible and seldom convenient. There is a need for practical techniques which would determine useful properties of an EM environment from relatively few measurements. One recent suggestion for such a technique is to use directional measurements at a single point in conjunction with a plane-wave expansion of the field. This paper reports the formulation of the technique and the results of a simulation using it.
[Contact: (303) 497-3150]

Randa, J., and Kanda, M., **A Directional Scanning Technique for Characterization of Complex Electromagnetic Environments,** Symposium Digest of the IEEE/AP-S International Symposium 1985, Antennas and Propagation, Vancouver, B.C., June 17-21, 1985, pp. 521-524.

The problem of characterizing complicated electromagnetic (EM) environments without actually measuring the field(s) throughout the entire volume of interest is of great practical importance in the areas of EM interference, EM compatibility, EM hazard assessment, etc. The question is how to obtain useful information about the volume of interest from a reasonably small number of measurements.

A recent suggestion which appears to hold considerable promise is to use a directional probe to measure at one point the field incident from different directions and then to reconstruct or bound the field throughout the volume by using these measurements in conjunction with a plane-wave expansion of the field. The formulation has now been completed and simulations performed for the (vector) electric field, and the results are reported in this paper. Simulation results are encouraging.
[Contact: (303) 497-3150]

Randa, J., and Kanda, M., **A Finite-Element Action Approach to the Characterization of Complex Electromagnetic Environments,** Proceedings of 1985 International Symposium on Antennas and EM Theory, Beijing, China, August 26-28, 1985, pp. 48-53.

An approach is outlined to the characterization of complicated electromagnetic environments based on a finite-element approximation to the action functional of the electromagnetic field. A stationary point of the action is found by a numerical search, subject to constraints imposed by boundary conditions and by measurements of the field at some number of points. The technique is illustrated by a simple example.
[Contact: (303) 497-3150]

Randa, J., and Kanda, M., **High-Frequency Errors of an Electric-Field Meter in Complicated Environments,** Proceedings of the 1985 IEEE International Symposium on Electromagnetic Compatibility, Wakefield, Massachusetts, August 20-22, 1985, pp. 618-621 [related paper, **Multiple-Source, Multiple-Frequency Error of an Electric Field Meter,"** appeared in IEEE Transactions on Antennas and Propagation, Vol. AP-33, No. 1, pp. 2-9 (January 1985)].

The results of a study of electric-field-meter (EFM) errors in complex electromagnetic environments are reported. Two types of errors are considered -- errors in the measured electric field for a common EFM design, and errors in the assumption of equal electric and magnetic energy densities in a multiple-plane-wave environment. Typical errors in both cases are approxi-

Electromagnetic Interference, cont'd.

mately one-half to three dB, but in some circumstances, they can exceed ten dB. [Contact: (303) 497-3150]

Wilson, P.F., and Ma, M.T., **Factors Influencing Material Shielding Effectiveness Measurements,** Proceedings of the IEEE 1985 International Symposium on Electromagnetic Compatibility, Wakefield, Massachusetts, August 20-22, 1985, pp. 29-31 [related paper, **"Shielding Effectiveness: Measurement Techniques and Interpretations,"** to be presented at 1986 Regional EMC Conference, Anaheim, California, February 6, 1986, and to be published in that conference's proceedings].

A material's shielding effectiveness is often measured in terms of insertion loss, the field reduction between a transmitter and receiver achieved by introducing the shield material. The insertion loss concept is simply stated; however, ambiguities arise when one attempts to interpret specific insertion loss measurements. Insertion loss data depend not only on the shield material tested, but also on the measurement procedure. The antenna types used and their positioning, the incident waveform and its wave impedance, and the contact resistance between the test material and its mount (if any) can all affect insertion loss measurements, sometimes dramatically. These concepts are discussed based on the simple model of coupling through an electrically small aperture, loaded and unloaded, with the shield material. Emphasis is on the importance of understanding and recognizing these factors when obtaining or interpreting shielding effectiveness results.
[Contact: (303) 497-3842]

1986 CEEE Calendar

June 23-27 (Gaithersburg, MD)

1986 CPEM (Conference on Precision Electromagnetic Measurements). CPEM 86 is being sponsored by the U.S. National Bureau of Standards, the IEEE Instrumentation and Measurement Society, and the Union Radio Scientifique Internationale. The Conference will present papers covering the theory, design, performance, simulation, and application of electromagnetic standards, measurements, techniques, instruments, and systems. Sessions are tentatively planned to cover the following technical areas: electromagnetic-related fundamental constants and standards; direct current, low frequency, and radiofrequency; time, time interval, and frequency; antennas and fields; microwaves and millimeter waves; infrared, visible, and ultraviolet radiation; lasers; electro-optics and fiber optics; cryoelectronics; automated measurements; and technical calibration services. The Conference language will be English. [Contact: Sara Torrence, (301) 921-2721. (For technical information, contact John R. Sorrells, (301) 921-2727 or Norman B. Belecki, (301) 921-2715.)]

September 9-10 (Boulder, CO)

Symposium on Optical Fiber Measurements. This fourth biennial Symposium is devoted to measurements on optical fiber, related components, and systems. It is sponsored by NBS in cooperation with the IEEE Optical Communications Committee and the Optical Society of America and is intended to provide a forum for reporting the results of recent measurements research and for evaluating these results in terms of future directions. About one-quarter of the sessions will be workshops led by invited panelists. Summaries of presented papers will be published in a technical digest to be distributed at the Symposium.
[Contact: Susie A. Rivera, (303) 497-5342]

RECENTLY ISSUED STANDARD REFERENCE MATERIALS

The first practical superconducting standard reference material (SRM) has been released by the Electromagnetic

Recently Issued SRMs, cont'd.

Technology Division to the NBS Office of Standard Reference Materials for sale to the public. The certified parameter of SRM 1457, Superconducting Critical Current -- NbTi Wire, is critical current at magnetic fields of 2, 4, 6, and 8 tesla at a temperature of 4.2 K and an electric field criterion of 0.2 μV/cm. Information is given to permit the user to determine critical current for temperatures in the range 3.90 to 4.24 K and electric field criteria from 0.05 to 0.2 μV/cm.

SRM 1457 consists of a 2.2-m length of a multifilimentary, niobium-titanium, copper-stabilized wire, wound in a single layer on a spool having a core diameter of 8.7 cm. The wire is evaluated for 34 parameters relating to current, voltage, magnetic field, temperature, strain, and physical specimen characteristics.

In conjunction with ASTM Standard Test Method B714-82, D-C Critical Current of Composite Superconductors, the new SRM is intended to provide means for calibrating apparatus used to measure key parameters of superconductor products and thus should be useful to buyers and sellers of superconductors, users of superconducting equipment, and researchers in superconducting technology.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

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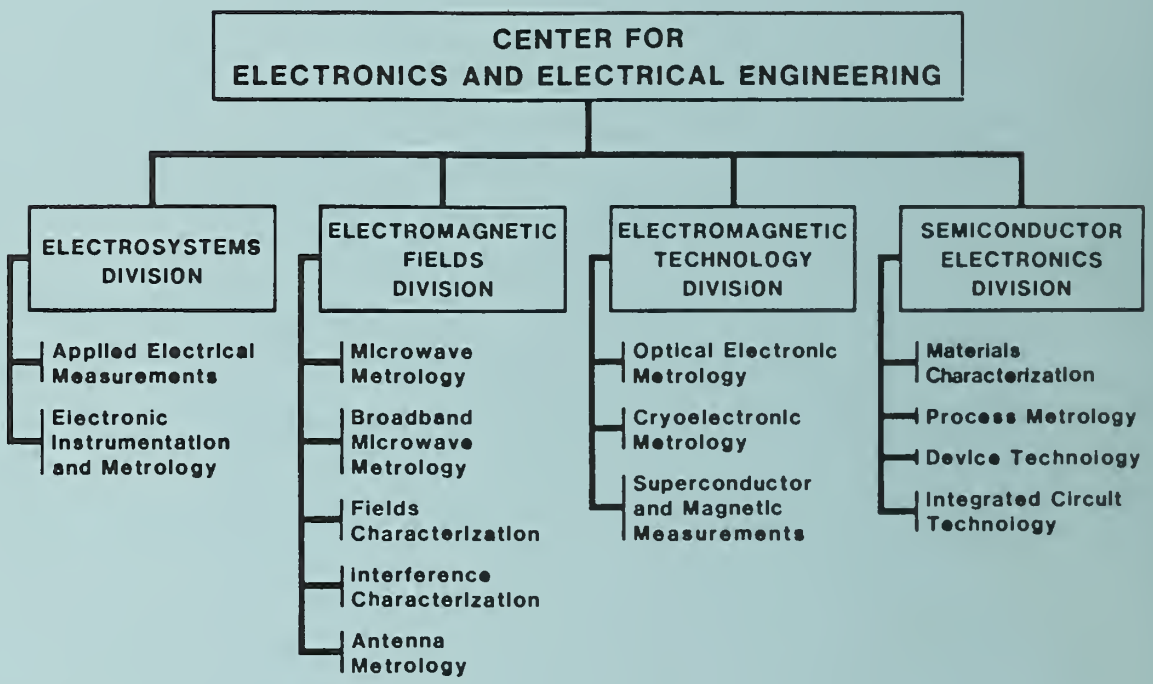

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